Discussion

The two processes that increase the salinity of the deep water, salt finger mixing and deep water formation events, have different signatures. Salt fingers transport heat, salt and density downwards making the deep waters warmer, saltier and denser. We expect the salt finger processes to be steady in the sense that the stratification with warmer saltier LIW above colder fresher WMDW enables salt finger processes to proceed year-round. On the other hand, deep water formation events are sporadic, occurring in late winter and only in severe winters. New deep water initially has a salinity close to the column average salinity in the formation region of the northwest Mediterranean because the wintertime formation events are not of long enough duration to appreciably change the salinity over a water column 2500 m thick (Smith et al., 2008). At the onset of deep convection, the temperature of the new deep water must be that temperature that combines with the water-column average salinity to equal or just exceed the density of the existing deep water (Leaman and Schott, 1991). As severe winter heat loss (mostly due to evaporation) continues, the new deep water can become colder and slightly saltier and denser, but mostly colder. Thus, deep water formation leads to saltier and warmer deep water only if the column-average salinity in the formation region is increasing.

The presence of high salinity LIW is critical to both processes. It sets the deep stratification where warmer saltier intermediate waters lie above colder fresher deep waters that is conducive to salt finger processes. Also, high salinity LIW preconditions the water column in the deep water formation region so that severe winter heat losses can mix down through the LIW and generate new deep water (Schroeder et al., 2010). The source of LIW is in the eastern Mediterranean, its core salinity in the western Mediterranean has increased by about 0.10 since the 1960's (Figure 2a) and this increase in LIW salinity is ultimately the cause of the saltier deep water in the western Mediterranean.

It is notable that the density of the Mediterranean intermediate and deep waters in the western Mediterranean at station A has not changed much over the past 50 years (Figure 2c). The core of LIW has had a potential density of about 29.07 since the 1960's. Deep water potential density has remained about 29.11 since the 1960's, with perhaps a small change to 29.12 in the 2005 deep water formation and maybe to 29.13 in the 2012 deep water formation event (Durrieu de Madron et al., 2013). Vertical mechanical mixing of new bottom waters with slightly less dense waters above gradually erodes the initially higher density of the deep waters so that over time there has been effectively no increase in deep water density. Temperature and salinity have increased but the density has stayed nearly constant as the temperature and salinity changes compensate in density. In terms of processes, the constancy of deep density is an argument for deep water formation events as the dominant source for increases in deep salinity because salt finger processes should lead to an increase in deep density as well as to increases in salinity and temperature. However, the increase in deep density associated with salt finger mixing is very small, amounting to only 0.004 kg m^{-3} per decade according to Bryden et al. (2014) so that over 50 years the deep potential density would have increased by only 0.02 kg m^{-3} and that change would be beyond our uncertainty in comparing surveys across 50 years.

That the density of Mediterranean water has not changed by very much over 50 years is contrary to Rohling and Bryden's (1992) arguments for the increasing salinity of the Mediterranean. They argued that the salinity of the Mediterranean is set by hydraulic control processes determining the maximum exchange for the flows between the Atlantic and Mediterranean through the Strait of Gibraltar. Their hypothesis was that increasing net evaporation (due to reduced river run-off) must ultimately lead to an increase in Mediterranean salinity and density that allows a stronger exchange flow through the Strait to balance the higher net evaporation. Rohling and Bryden (1992) were actually arguing that an increase in density of the Mediterranean water by about 0.2 kg m^{-3} was necessary to enable a stronger exchange flow to balance the increased net evaporation. No such sizeable increase in density has in fact been observed over the past 50 years since the damming of the Nile River.

Prior to 1969, the salinity of the deep water in the western Mediterranean was apparently in steady state (Lacombe et al., 1985) allowing oceanographers to assume steady state processes. For the Mediterranean Sea we traditionally use steady state heat and salt conservation statements for the Mediterranean basin with inflow and outflow through the Strait of Gibraltar at Atlantic and Mediterranean water salinities to derive the Knudsen relationships that quantify the size of the inflow and outflow as a function of the net evaporation over the Mediterranean. Bryden and Kinder (1991) added steady hydraulic theory to the heat and salt conservation statements to show how the salinity of the Mediterranean could be determined as a function of the net evaporation over the Mediterranean.

But the Mediterranean Sea is clearly not in a steady state: temperature and salinity have been rising steadily since the 1960's; river run-off has been reduced as rivers are dammed and used for irrigation; and models suggest evaporation is increasing due to the warming climate. Adjusting our steady state views of the Mediterranean requires careful consideration of the time dependent heat and freshwater budgets. For example, how can we modify the Knudsen relations for the Gibraltar exchange for an increasing net evaporation and an increasing salinity of the Mediterranean?

Will the Mediterranean ever reach a steady state in response to global warming and the changing water balance associated with increased evaporation and reduced river run-off? How long can the salinity of the Mediterranean continue to increase? What value will it achieve? Answering these questions represents a challenge for the Mediterranean modelling community and validating the model predictions will require continuing observations of the deep Mediterranean Sea.